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Explosives Ordnance Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

A study of the detonation performance of the insensitive explosive filling, PBXW-115 (Aust.), has been undertaken and the results compared to those from its American counterpart, PBXW-115 (USA) / PBXN-111, an explosive of the same nominal composition but formulated with bimodal RDX of different type and somewhat differing particle size distribution.

The limiting value of the velocity of detonation at infinite diameter, D, of PBXW-115 (Aust.) is in the range 5.64-5.91 km s^{-1}, the actual value depending on the assumed relationship between the experimental V of D and the diameter of the charge. This range of values is slightly less than that calculated for PBXW-115 (USA), 5.76 - 6.19 km s^{-1}, using experimental data reported by Forbes et al. (1989).

The major differences between the results from the two formulations , however, relate not to values of D but to critical diameter and to relative shock sensitivity (as measured in the Large Scale Gap Test).

The critical diameter of unconfined PBXW-115 (Aust.) is ca. 80 mm; that of PBXW-115 (USA) is 38 ± 2 mm; the differences are not as pronounced in charges confined in brass tubes, however -- 24 ± 2 mm (3 and 5 mm thick brass tubes) for PBXW-115 (Aust.) vs. 21 ± 2 mm (2.5 mm thick brass tubes) and 17 ± 2 mm (5 mm thick brass tubes) for PBXW-115 (USA).

The shock sensitivity of PBXW-115 (Aust.) is 6.3 GPa, the explosive shock wave pressure which has been determined experimentally to result in a 50 % probability of detonation in the Large Scale Gap Test. The corresponding figure for the US formulation is 4.7 GPa.

Reasons for these differences are advanced.

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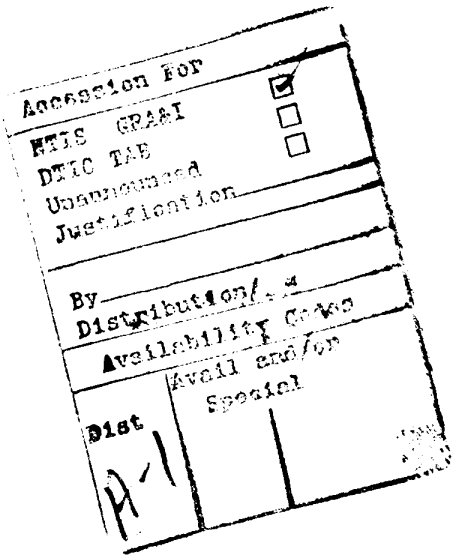

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The Critical Diameter, Detonation Velocity and Shock Sensitivity of Australian PBXW-115

EXECUTIVE SUMMARY

PBXW-115 is a polymer bonded explosive (PBX) which was developed at Naval Surface Warfare Center, White Oak, Silver Spring, MD, USA in the late 70s/early 80s, for potential use as an insensitive explosive fill for underwater applications. Since that time, PBXW-115 has been fully qualified and has been introduced into service as PBXN-111. More recently, an Australian version, PBXW-115 (Aust.), has been produced and this is being investigated for possible adoption by the Royal Australian Navy as a warhead fill for future mine demolition shells. This report elaborates on the experimental approach to the study of the explosive performance of PBXW-115 (Aust.).

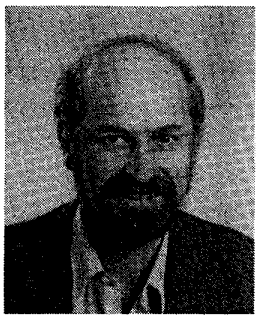
It details experiments designed to measure the velocity of detonation (V of D) of unconfined and confined PBXW-115 (Aust.), to establish its critical diameter and to determine its shock sensitivity. A number of specific experiments were also carried out to investigate the effect of changes in mean particle size of RDX on the V of D of confined charges of PBXW-115 (Aust.) and to ascertain the effect of changes in charge porosity/charge density on its shock sensitivity.

The limiting value of the velocity of detonation at infinite diameter, D, of PBXW-115 (Aust.) is 5640 m s^{-1}, its unconfined critical diameter is ca. 80 mm, a very high value, and its shock sensitivity, as measured in the AMRL Large Scale Gap Test (LSGT), is 6.3 GPa. The corresponding values for the US formulation are D of 5760 m s^{-1}, critical diameter of 38 mm, and LSGT shock sensitivity of 4.7 GPa. On the basis of these data, it is likely that PBXW-115 (Aust.) will display an enhanced IM performance when compared to its US counterpart.

Reasons for these differences are advanced. It would appear that the source of the differences resides in the characteristics of the bimodal RDX used in the formulations. Experimental results indicate that RDX type, class, particle size distribution and compatibility of particle shapes all play a role in determining the explosive performance of the basic formulation.

In an investigation peripheral to the original objectives addressed in this paper, the authors have found that there is a simple relationship between the reaction zone length of a detonating heterogenous RDX-driven explosive and its critical diameter and this has extended one's ability to predict explosive performance data on the basis of a smaller number of experiments.

Authors



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Explosives Ordnance Division

Gunter Bocksteiner graduated from Footscray Institute of Technology in Applied Chemistry and joined AMRL in 1968. He has worked widely within AMRL, initially on the mechanistic chemistry of chemiluminescent materials, then biologically active surface coatings and the effects of the marine environment on defence materiel. In 1980 he commenced work on determination of explosives hazard, and lately has been working on polymer bonded explosives formulations.

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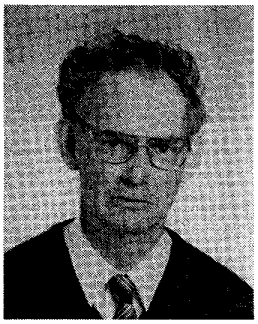
Mike Wolfson has gained extensive experience in over thirty years working exclusively in the explosives R & D field in both England and Australia. He joined AMRL in 1964, working initially on explosives formulation, and device development and testing, and later on the measurement of detonation parameters. He is a specialist in the application of electronic and photoinstrumentation techniques for determining the performance and effects of explosives and munitions. His publications cover a diverse range of topics from explosives polishing techniques to ship shock testing.



D.J. Whelan
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Dan Whelan joined AMRL in 1968 and worked in various areas of Organic Chemistry Division before transferring to the forerunner of Explosives Ordnance Division in 1980. His current interests are in explosives performance, underwater explosives, thermal analysis, solid state reaction kinetics and practical data correlations. He recently joined the Editorial Board of the Journal of Energetic Materials.

Contents

Glossary of Symbols and Abbreviations

Symbol	Descriptor
V of D	Velocity of detonation
V(d)	Velocity of detonation at a charge diameter, d.
D	Velocity of detonation at infinite charge diameter; mathematically, $V(\infty) = D$.
LSGT	Large Scale Gap Test
δ	Nmr Chemical Shift, relative to tetramethylsilane, TMS
d_c	Critical charge diameter or critical diameter; sometimes called failure diameter.
(1 / d)	Reciprocal of charge diameter
a	Eyring reaction zone length parameter; a mathematical constant, characteristic of the explosive formulation defined by Eq. 11, in the text.
a*	Elliptical reaction zone length parameter; a mathematical constant, characteristic of the explosive formulation defined by Eq. 15, in the text.
LLSQ	Linear Least Squares

1. Introduction

PBXW-115 is a polymer bonded explosive (PBX) which was developed at Naval Surface Warfare Center, White Oak, Silver Spring, MD, USA in the late 70s / early 80s, for potential use as a low cost insensitive explosive fill for underwater applications [1]. Since that time, PBXW-115 has been fully qualified and introduced into service as PBXN-111 [2]. More recently, an Australian version of the US formulation has been produced and investigated [3,4] for possible adoption by the Royal Australian Navy and it has been found that the explosive performance properties of this Australian version are sufficiently different from those of its American counterpart to warrant some form of differentiation [4]. For this reason, throughout this report, the Australian formulation will be referred to as PBXW-115 (Aust.) and the American formulation, PBXW-115 (USA).

This report elaborates on the experimental approach to the study of the explosive performance of PBXW-115 (Aust.) and attempts to explain the possible origin of the observed differences in explosive performance between the US and Australian compositions.

It details experiments designed to measure the velocity of detonation (V of D) of unconfined and confined PBXW-115 (Aust.), to establish its critical diameter and to determine its shock sensitivity. A number of specific experiments were also carried out to investigate the effect of changes in mean particle size of RDX on the V of D of confined charges of PBXW-115 (Aust.) and to ascertain the effect of changes in charge porosity / charge density on its shock sensitivity.

The report complements those of Anderson and Leahy [1] and Forbes et al. [5] on PBXW-115 (USA), Bocksteiner and Billon [3] on the formulation and hazards assessment of PBXW-115 (Aust.) and Jones and Kennedy [6,7], who have applied the computer code, CPEX (Commercial Performance of Explosives) of Kirby and Leiper [8], to the V of D results of PBXW-115 of both Australian and American origin.

2. Experimental

2.1 Formulation

PBXW-115 is cast cured with a nominal composition of bimodal RDX (20%), ammonium perchlorate, AP (43%), aluminium, Al (25%), in a hydroxy-terminated polybutadiene (HTPB) / isophorone diisocyanate (IPDI) polyurethane (PU) binder (Table 1).

Table 1: Formulation of PBXW-115 (USA) [1]

Component	Mass (%)	Binder (%)
Ammonium perchlorate	43	
Aluminium X81	25	
RDX Class 1 [USA nomenclature] (standard, fine)	12	
RDX Class 5 [USA nomenclature] (very fine)	8	
Hydroxyl terminated polybutadiene	5.7	47.5
Isodecyl pelargonate, plasticiser	5.7	47.3
Isophorone diisocyanate, cross-linking agent	0.54	4.72
4,4'-Methylene-bis(2,6-di-t-butyl- phenol), antioxidant	0.05	0.42
Dibutyltin dilaurate, PU cross-linking catalyst	0.004	0.06

The theoretical maximum density of PBXW-115 is 1.80 Mg m^{-3}.

There appear to be only small differences between the Australian formulation and the American version and these have been described previously [3]. The principal difference appears to be in the nature of the bimodal RDX component of the formulation.

In the American version, the bimodal RDX mixture is made up from RDX, Type II, Class 1 (60%) and RDX, Type II, Class 5 (40%) [1] and has an overall median particle size calculated to be 60 μm [Page 2 of Ref. 2].

The Australian version of PBXW-115 is made with Australian-manufactured RDX, Grade A (recrystallized, from Albion Explosives Factory and made by the Woolwich or nitric acid process), Class I , (60%) and ROF, Bridgewater, UK-manufactured RDX, Type II , Class 5 (40%); its overall median particle size has been calculated to be 105 μm.

Both the American RDX, Type II and the ROF, Bridgewater RDX, Type II, Class 5 are made by the Bachmann or acetic anhydride process, which typically yields 5 -12% HMX as a by product. RDX, prepared by the Woolwich process, does not contain HMX [9].

2.2 Materials

2.2.1 RDX

As indicated in Section 2.1, all the fine particle-sized RDX used in this work was ROF, Bridgewater, UK - manufactured RDX, Type II , Class 5 [Mix B5 M038, Lot BGW 300].

This material was inappropriately labelled RDX, Gr. E, but the specification and the subsequently determined physical characteristics (Fig. 1) confirmed its Type and Class.

The U.S. specifications for RDX, Type II, Class 1 and the Australian specifications for RDX, Grade A (recrystallized) Class 1 are similar [10,11]. For US Class 1 RDX, a minimum 65% (by mass) of the particles, denoted by the symbol x in the following expression, must be in the range 300 μm > x > 75 μm; for Australian Class 1 RDX, the specification calls for a minimum of 67% over the same size range.

Various batches of RDX, Grade A Class 1, the coarser component of the bimodal blend of RDX used in the preparation of PBXW-115 (Aust.), were used in these experiments.

For the unconfined V of D measurements on PBXW-115 (Aust.), the RDX Grade A Class 1 component was from a single batch from Albion Explosives Factory, (AEF, Australian Defence Industries Pty. Ltd.), Lot 321 (Grade A). Its particle size / cumulative weight characteristics are given in Fig. 1 and correspond to those for 160 μm RDX Grade A.

For the confined V of D measurements where particle size effects were to be studied, the RDX Grade A Class 1 component was drawn from batches with different size distributions. The first batch was the same as that used in the unconfined V of D measurements, mean particle size 160 μm; the second batch was also from AEF, but it had a mean particle size of 260 μm, (Fig. 1).

To check for the presence or otherwise of HMX in the samples of RDX used in this work, the techniques of H^1-NMR spectroscopy were used.

300 MHz H^1-NMR spectra were measured for samples of research grade HMX, Grade B, the two samples of RDX Grade A from AEF (one with a mean particle size 160 μm, the other with a mean particle size 260 μm) and RDX, Type II, Class 5 , from ROF, Bridgewater - perdeuterodimethyl sulfoxide (DMSO-d_6) as solvent, sample concentration ca. 10 mg / mL [12]. The ^{1}H-NMR spectrum of HMX consisted of a single sharp peak, at a chemical shift, δ, of 6.01 ppm attributable to the (N-CH_2-N) protons in HMX. The spectrum of the Australian-made RDX consisted of just a single peak slightly downfield from that of HMX, at 6.09 ppm, with no trace of HMX discernible at the signal intensity level of the spinning side bands (ca. 0.6% of the intensity of the RDX signal). On the other hand, the spectrum of the RDX, Type II contains both the main RDX peak at 6.09 ppm and a small peak at 6.01 ppm (6-6.5% of the intensity of the RDX signal) attributable to HMX. This level of HMX in RDX is similar to that quoted for samples of RDX of unspecified origin by van den Steen and Verbeek in their study of the initiation and detonation of RDX/HTPB-based PBXs [13].

2.2.2 AP, Al and Binder Components

Source of supply and methods employed in characterisation of AP, Al and binder components (IPDI, TMXDI, HTPB liquid resins, IDP plasticizer, Ethanox 702 and DBTDL) have already been reported [3].

Particle size / cumulative weight data for AP and Al have been plotted in Figure 1. The median particle size of the Al used in PBXW-115 (Aust.) is ca. 20 μm, whereas in PBXW-115 (USA), it is 5 μm; the median particle size of AP in both formulations is ca. 200 μm.

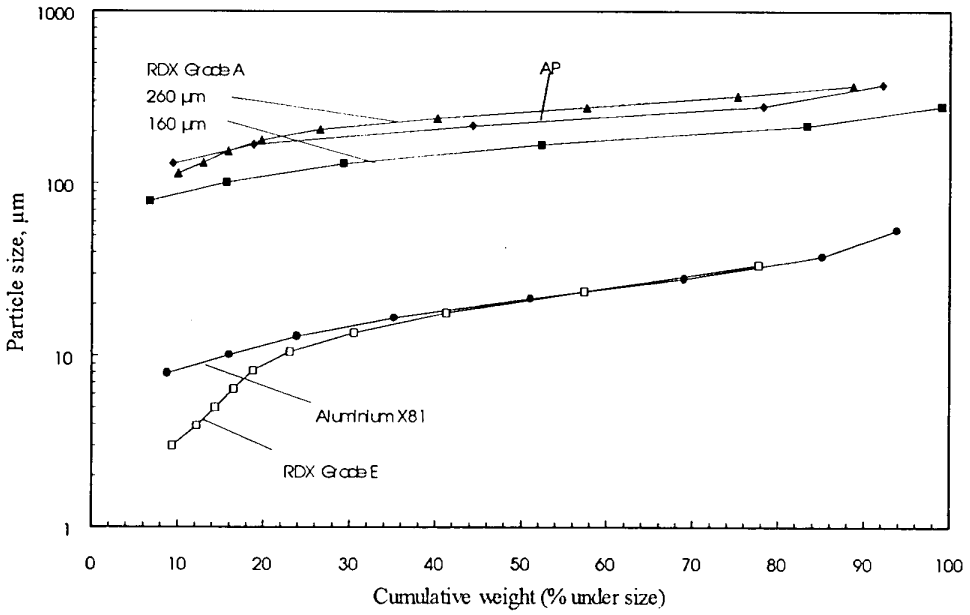

Figure 1: Particle size distribution for RDX Grade A (160 and 260 μm median size), E (20 μm median size), Al X81 and AP, as determined by Malvern Particle Size Analyser.

2.3 Processing of PBXW-115 : Mixing and Casting

All the RDX used in the PBXW-115 (Aust.) formulation was dried prior to use. Mixing, casting and density determinations were carried out following standard procedures [3].

High quality cast charges of high density (>1.79 Mg m^{-3}) were used for V of D and LSGT measurements. Lower density cast charges (≤ 1.70 Mg m^{-3}, which is ≤ 95% TMD) resulting from either included air bubbles or moisture-generated bubbles of

CO_2 were also used for LSGT measurements to determine what effect increased porosity has on shock sensitivity at this level. Unconfined and confined charges were cast into items as described in Sections 2.4.2 and 2.4.3, below.

2.4 Critical Diameter (d_c) and Velocity of Detonation (V of D)

2.4.1 Critical Diameter

The critical diameter of an explosive is the minimum diameter which will sustain a stable detonation; it is a threshold dimension below which detonation cannot be sustained [14]. Unconfined and confined critical diameters were determined directly by inspecting the experimental distance / time data and examining the witness plates.

2.4.2 V of D of Unconfined Charges of PBXW-115 (Aust.)

At AMRL, the V of D of an explosive charge is commonly measured by high speed streak photography or ionisation probe techniques. In this work ionisation probe methods were used.

Unconfined charges with diameters from 30 to 80 mm were prepared by casting the mixed ingredients into epoxy-lined cardboard cylinders, fitted with 10 hypodermic needle insulated copper wire ionisation probes inserted at set intervals. The inter-probe distances for 60, 70 and 80 mm diameter charges were set at 20, 25 and 30 mm respectively.

Unconfined charges with diameters of 110, 140, 170 and 200 mm were prepared by casting the mixed ingredients into stackable epoxy lined cardboard cylinders, each cylinder having explosive content of 0.65, 1.4, 2.8 and 4.3 kg for the respective charge diameters. The ends of these cylinders were machined to allow for accurate interface measurements using vernier callipers. Two brass strips 5 mm wide and 0.05 mm thick were placed 4 mm apart across these interfaces to act as ionisation probes. Each charge had ten pairs of ionisation probes placed at interfacial distances ranging from 40 mm for the 110 mm diameter charge to 80 mm for the 200 mm diameter charge. All unconfined charge dimensions complied with the general accepted requirement that length be equal to five times diameter to allow for sufficient run in and stabilisation of detonation front.

Cylindrical 50/50 pentolite boosters of diameter and length equal to the diameter of the main charge were used to ensure reasonably planar shock waves entered the acceptor charges (Table 2). All boosters were initiated by exploding bridge-wire detonators (EBWs).

2.4.3 V of D of Confined Charges of PBXW-115 (Aust.)

Confined PBXW-115 charges were prepared by casting directly into steel and brass tubes sealed at the base with mylar plastic sheet. Each tube had five twisted insulated copper wire ionisation probes attached to its inner surface; the end of each probe was separated from its predecessor by a distance of 20 mm. To avoid any adverse effect on the degree of confinement of the explosive, the ionisation probes entered the brass and steel tubes from the base and were attached to the vertical sides of the tubes. The internal diameters of the tubes ranged from 22 mm to 50 mm and the wall thickness were either 3 mm or 5 mm. The tube lengths for the smaller diameter charges were 5 x diameter. A variety of booster types were used for the confined charges. All booster diameters were equal to the diameters of the acceptor charges.

2.5 Shock Sensitivity Measurements: Large Scale Gap Test (LSGT)

The LSGT used at AMRL [15] is based on the standard LSGT developed at NSWC for the determination of sensitivity of an explosive to initiation by shock [16].

Details of the AMRL test configuration are shown in Figure 2. The test sample is cast into a steel cylinder 38.1 mm inside diameter, 5 mm wall thickness and 139.7 mm length. One end is in contact with the shock attenuator, the other end has a 1.6 mm air gap between the steel witness plate and explosive. A modified Bruceton staircase procedure is used to determine the 50% probability of detonation where the criterion for a "go" (a detonation) is that a hole is punched through the witness plate.

3. Results

3.1 General Background

PBXW-115 is a composite explosive which can support a steady state detonation, both in the unconfined and confined state [5]. However, its observed explosive behaviour is such that it still behaves as a thermodynamically and kinetically "non-ideal" explosive at traditionally large (>25mm) unconfined charge diameters [17], where kinetic steps associated with the propagation of the shock wave are limited by the speed with which the fuel and the oxidant within the composition can be brought together and react [6].

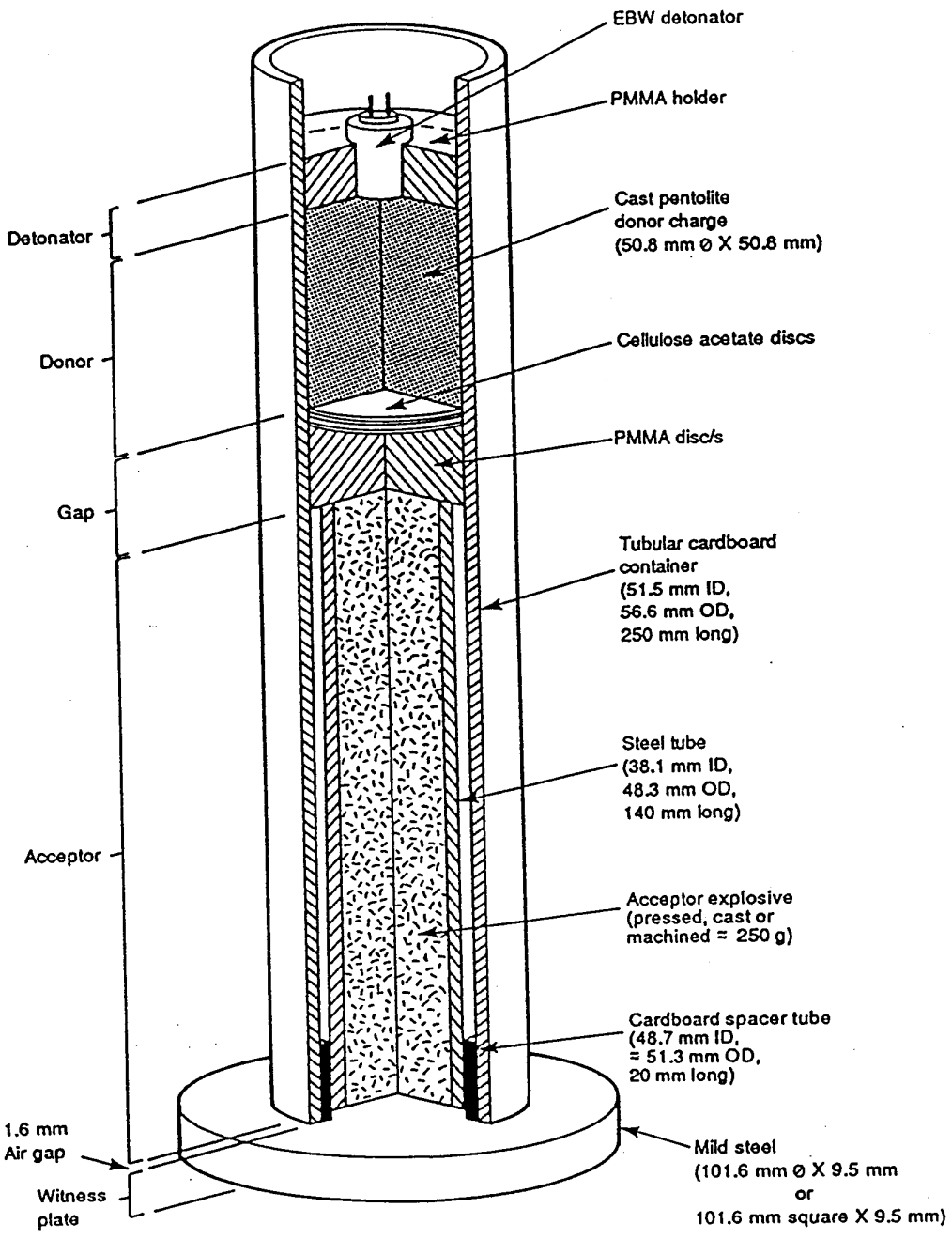

Figure 2: Test configuration of the LSGT used at AMRL

3.2 Performance Parameters

3.2.1 Critical Diameter of PBXW-115 (Aust.)

The results showing the effect of changes in charge diameter on the observed V of D of unconfined PBXW-115 (Aust.) are summarised in Table 2. Even from the limited number of shots, it is apparent that the critical diameter of PBXW-115 (Aust.) is approximately 80 mm (1 Go / 1 No Go), a value very much greater than that reported for its US counterpart, 37.6 ± 1.6 mm, [2,5] and one which will be discussed later.

The effect of confinement in brass, a material of high acoustic impedance (the product of the density of the confining medium and its sound velocity) is shown in Table 3. For both 3 and 5 mm thick cylindrical brass tubing with charge lengths up to 300 mm, the critical diameter of PBXW-115 (Aust.) is between 22 mm and 26 mm. This is in contrast to the results for PBXW-115 (USA), where confinement in brass tubing, 2.5 mm thick, results in a critical diameter of 21 ± 2 mm and confinement in 5 mm thick brass tubing results in a critical diameter of 17 ± 2 mm [5].

Table 2: The effect of charge diameter, d, of unconfined PBXW-115 (Aust.) on Velocity of Detonation

Shot No.	Density	Booster Mass, kg	Charge Mass, kg	Charge Diameter d, mm	Charge Length, mm	V of D, m s^{-1}	Standard Deviation, m s^{-1}
1	1.791	0.28	1.5	60	300	Failed	-
2	1.792	0.45	2.3	70	335	Failed	-
3	1.794	0.45	2.4	70	340	Failed	-
4	1.793	0.66	3.75	80	430	Failed	-
5	1.79	0.66	3.35	80	390	5072	5.0
6	1.79	1.70	9.5	110	560	5372	6.1
7	1.79	1.70	9.2	110	550	5306	4.1
8	1.79	3.60	18.5	140	700	5476	3.5
9	1.79	3.60	18.5	140	700	5445	2.0
10	1.79	6.40	33.6	170	850	5525	3.9
11	1.79	10.4	55.6	200	1000	5557	3.5

These sets of data indicate that both PBXW-115 (Aust.) and PBXW-115 (USA) will sustain stable detonation in their respective LSGT configurations [1,15,16]; the diameter of the charges in the LSGTs, 38.1 mm, exceeds the confined critical diameters by a considerable factor.

Table 3: The effect of brass confinement, charge diameter, d, and the particle size of the RDX Grade A component of PBXW-115 (Aust.) on its Velocity of Detonation

Expt No.	Brass Tube Thickness, mm	RDX Size, μm	Booster Type	Charge Diameter, d, mm	V of D, m/s	Standard Deviation, m/s
11C	3	160	Tetryl	22	failed	-
10C	3	160	PE 4	26	5045	44
8C	3	160	PE 4	32	5170	45
6C	3	160	Tetryl	38	5265	19
4C	3	160	Tetryl	42	5305	35
2C	3	160	Pentolite	50	5320	47
11D	5	160	Tetryl	22	failed	-
1D*	5	160	PE 4	26	5070	12
2D	5	160	PE 4	26	5140	38
3D*	5	160	PE 4	32	5090	41
4D	5	160	PE 4	32	5205	47
5D*	5	160	Tetryl	38	5245	140
6D	5	160	Tetryl	38	5215	44
7D*	5	160	Tetryl	42	5305	31
8D	5	160	Tetryl	42	5285	54
9D*	5	160	PE 4	50	5300	22
10D	5	160	Pentolite	50	5395	32
9C†	3	260	PE 4	26	5005	138
7C†	3	260	Tetryl	32	4965	82
3C†	3	260	Tetryl	42	5005	25
BR1†	3	260	Tetryl	44	5120	40
1C†	3	260	Pentolite	50	5170	30

* The binder in these charges was cured with TMXDI in place of IPDI.

† The mean particle size of the RDX Grade A used in the formulation of these shots was 260 μm, not the standard 160 μm material.

3.2.2 Velocity of Detonation of Unconfined PBXW-115 (Aust.)

The data relating V of D to charge diameter for PBXW-115 (Aust.) listed in Table 2 can be analysed in various ways.

One of the more common presentations, namely the plot of V of D, (m s^{-1}) vs. 1 / d, the reciprocal of charge diameter, (m^{-1}), is given in Figure 3. A straight line can be fitted to the data using a linear least squares analysis, resulting in an Eyring-type relationship [14],

$$V(d) = -65.33\ (1 / d) + 5913 \qquad \text{[Eq. 1]},$$

with a linear least squares (LLSQ) coefficient of determination 0.968, for charges of diameters from 0.080 m to 0.20 m (80 mm to 200 mm); here, V(d) is the mathematical abbreviation for V of D at a charge diameter, d.

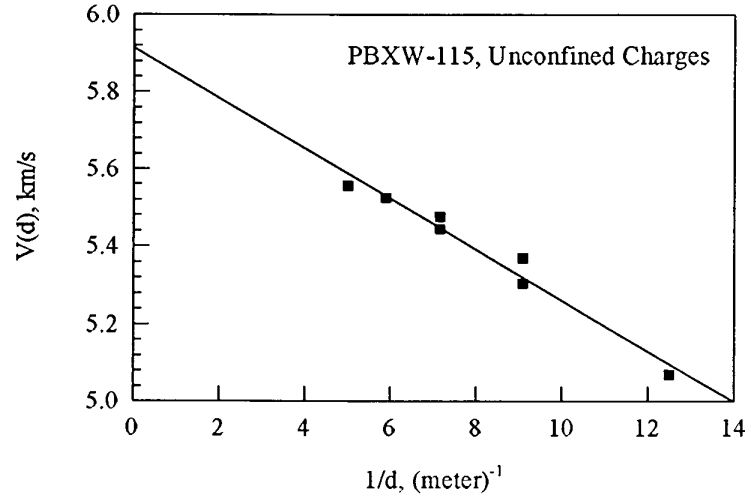

Figure 3: Plot of V of D vs (1 / d) for unconfined charges of PBXW-115 (Aust.).

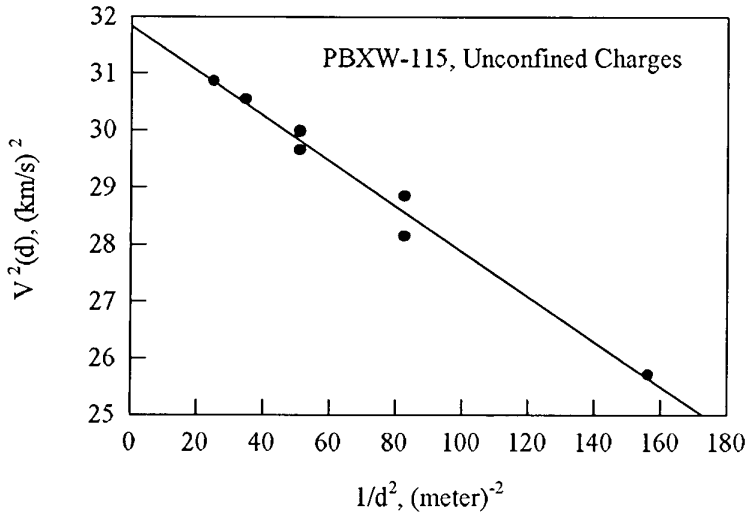

Figure 4: Plot of (V of D)² vs. (1 / d)² for unconfined charges of PBXW-115 (Aust.).

However, close inspection of the experimental data suggests that, at larger charge diameters (140 - 200 mm), the V of D appears to be approaching a limiting value of the V of D at infinite charge diameter which is somewhat less than that extrapolated from [Eq.1].

A linear least squares plot of $(V \text{ of } D)^2$ as a function of $(1 / d)^2$, as shown in Fig. 4, gives a better fit - following the equation

$$(V(d))^2 = -39560\ (1 / d)^2 + (5642)^2 \qquad \text{[Eq. 2]}$$

with a LLSQ coefficient of determination of 0.983.

From Eq. 2, it can be deduced that, using the experimentally-determined data from charges of PBXW-115 (Aust.) up to 0.20 m (200 mm), the calculated limiting V of D, or D, is 5642 m s^{-1}.

Similar departures from linearity in plots of V of D vs. (1/d) have been observed many times, for instance, in RDX (70%) / PU Binder (30%) PBX compositions [18-20], in Composition B [21], in the HMX-containing PBX-9404 [22] and in an RDX emulsion explosive [23]. In all of these cases, the data can be fitted much more satisfactorily to a linear least squares elliptical relationship, plotting $(V \text{ of } D)^2$ vs. $(1/d)^2$, than to the simple linear relationship between V of D and (1/d).

A similar treatment of the NSWC data [5] for charges of PBXW-115 (USA) of diameters ranging from 0.0387 m to 0.0691 m (38.7 mm to 69.1 mm) yields the corresponding equations,

$$V(d) = -42.42\ (1 / d) + 6193.4 \qquad \text{[Eq. 3]}$$

with a LLSQ coefficient of determination of 0.908, for the linear relationship between V of D and inverse diameter, and

$$(V(d))^2 = -11140\ (1 / d)^2 + (5759.9)^2 \qquad \text{[Eq. 4]}$$

with a LLSQ coefficient of determination, 0.968, for the elliptical relationship between these two parameters.

In order to marry the results obtained from these two PBXW-115 formulations, Jones and Kennedy [6], following Campbell and Engelke [24] and Leiper and Cooper [25,26], suggested plotting the observed V of D (m s^{-1}) vs. the dimensionless parameter, (d_c / d) where d_c is the critical diameter of the particular formulation of PBXW-115 under consideration. These plots yield a relationship of the form

$$V(d) = -875.28\ (d_c / d) + 5968.3 \qquad \text{[Eq. 5]}$$

with a LLSQ coefficient of determination 0.907, for the linear relationship between V of D and inverse diameter, and

$$(V(d))^2 = -6673550\,(d_c / d)^2 + (5671.6)^2 \qquad [\text{Eq.6}]$$

with a LLSQ coefficient of determination 0.942, for the elliptical relationship.

Based on these calculations, the value of D in PBXW-115 - type formulations, from the data to 200 mm, is in the range 5642- 5913 m s^{-1}. These results can be compared to a V of D figure, 5400 m s^{-1}, recently suggested by Held for a very similar German composition, presumably KS 57 , based on AP (40%) / RDX (24%) / Al (24%) / polybutadiene-based binder (12%) of density 1.8 Mg m^{-3} [27]. Whether this figure of Held represents the limiting V of D value or not is debatable but this matter will not be pursued here.

At this point, it suffices to say that in the charge diameter domain investigated in this paper, differences have been observed between PBXW-115 (Aust.) and PBXW-115 (USA).

In addition, Jones and Kennedy [6, 7] have suggested that the calculated values for D, which have been derived above by extrapolation, give values which are low because, at these charge diameters ($d << 5\ d_c$), the data only reflect reactions which result in the detonation of the RDX component of the PBX composition. This will be taken up more fully at a later stage in the report.

At these lower charge diameters, the detonation wave is definitely not driven by AP or reactions emanating directly from AP. This is supported by the findings of Price *et al.* and of Evans *et al.*, who found that it is only under forcing conditions that AP will detonate, that its V of D is quite low (3700 m s^{-1} at density 1.00 Mg m^{-3}) [28, 29] and that, some, if not all, simple RDX-free composite propellants containing 82% AP will not detonate in the standard LSGT [30]. It is generally accepted that AP based compositions, although very sensitive to ignition, are far more prone to deflagrate than to detonate [31-33].

Were V of D measurements on either PBXW-115 (Aust. or USA) carried out at much greater charge diameters, Jones and Kennedy have calculated that it should be possible to see the full effects attributable to the oxidation of Al by AP and its explosion products, as well as those from the detonation of RDX . One could then determine the true limiting value of V of D. There is an experimental and computational precedent for stating this.

In two heterogeneous explosive systems, one a commercial slurry explosive, the other a commercial nitroglycerine powder-based explosive, Leiper found that at very large charge diameters, ($d > 6\ d_c$), plots of V of D vs. $1/d$ or of $(V \text{ of } D)^2$ vs. $(1/d)^2$ based on experimental data, departed from linearity and, using the computer code, CPEX and a suitable Equation of State, he calculated that the magnitude of D should be much greater than the value estimated from extrapolation of these simple plots [26]. The analytical procedure adopted by Leiper has been the basis of Kennedy and Jones' approach estimating the actual value of D for PBXW-115; they have calculated a value for D in the range 6665 - 8010 m s^{-1} [6, 7], the actual value depending on just

what the detonation products are and which equation of state (either BKW or IDeX) best describes them. The IDeX equation of state leads to the 6665 m s^{-1} value, BKW to the 8010 m s^{-1} value.

3.2.3 Velocity of Detonation of Confined Charges of PBXW-115 (Aust.)

In Table 3, one can find the results of experiments carried out to determine the V of D of charges of diameters ranging from 25 mm to 50 mm of PBXW-115 (Aust.) confined in cylindrical brass tubes of thickness either 3 mm or 5 mm. These results are plotted in Fig. 5.

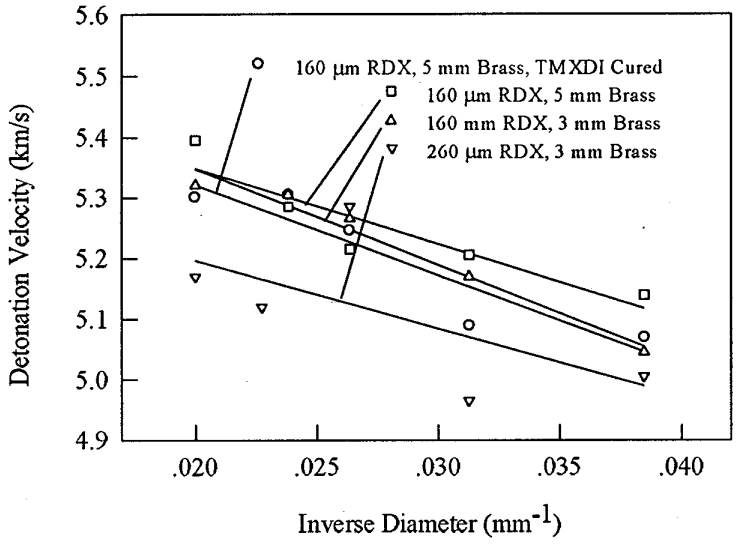

Figure 5: Plot of experimentally observed Velocity of Detonation versus Inverse Diameter (l/d, mm) for confined PBXW-115, showing the effect of degree of confinement in brass of different thickness and of the effect of changes in the particle size distribution.

There is considerable scatter in the experimental results and this precludes determination of D with the same degree of reliability as was achieved with the unconfined explosives. This is due to the fact that one is firing relatively small charges in a relatively high degree of confinement at diameters close to the critical diameter.

From an analysis of the data similar to that detailed above for the unconfined explosive, one can fit the data from the 3 mm thick brass confinement to either a linear relationship,

$$V\,[160,3] = -15.78\,(1 / d) + 5662 \qquad \text{[Eq. 7]}$$

with a coefficient of determination 0.972, 5 coordinates or an elliptical relationship,

$$(V\,[160,3])^2 = -2787\,(1/d)^2 + (5437)^2 \qquad \text{[Eq. 8]}$$

with a coefficient of determination 0.983 from 5 coordinates, where V [160,3], in m s^{-1}, is the velocity of detonation of PBXW-115 (Aust.) charges, diameter d meter, confined in 3 mm brass tubing. The '160 ' refers to the particle size (in microns) of the RDX Grade A component used in the formulation, and the '3', to the thickness of the brass tubing, (in mm).

Similarly, one can fit the data from the 5 mm thick brass confinement, thus:-

$$V\,[160,5] = -13.645\,(1/d) + 5607 \qquad \text{[Eq. 9]}$$

with a coefficient of determination 0.802 from 10 coordinates or

$$(V\,[160,5])^2 = -2347\,(1/d)^2 + (5408)^2 \qquad \text{[Eq. 10]}$$

with a coefficient of determination 0.762 from 10 coordinates.

These results include those obtained from PBXW-115 (Aust.) incorporating TMXDI-cured HTPB-based polyurethane binder rather than the IPDI-cured binder; there is no apparent effect on the measured V of Ds in changing the crosslinking agent from IPDI to TMXDI. Statistically, this latter pair of equations represent data which has a considerable scatter.

The values of D from Eqs. 7 and 9 (linear dependency) or from Eqs. 8 and 10 are equal within the limits of the experimental uncertainties but, unexpectedly, the values are somewhat lower than those obtained from the unconfined charge (Section 3.1.2).

In order to further define the possible effect of particle size distribution of RDX on the V of D, a batch of PBXW-115 (Aust.) was made up using RDX Grade A of mean particle size 260 μm as the coarse component in the bimodal RDX part of the formulation. The results of this study are also presented in Table 3 and reproduced in Fig. 5. In the range studied, the confined V of D is affected, the overall V of D from the formulation containing 260 μm RDX appearing to be somewhat less than that from the formulation containing 160 μm RDX. Whether this would be important in samples of larger diameter remains to be seen. The effects of particle size will be taken up in the discussion.

3.2.4 Shock Sensitivity of PBXW-115 (Aust.): LSGT

The results of Large Scale Gap Tests carried out at AMRL on PBXW-115 (Aust.) along with those from some other reference explosives are presented in Table 4. Some salient points emerge.

Table 4 : LSGT results for various batches of PBXW-115 (Aust.) and for relevant reference materials determined at AMRL and elsewhere

Batch Characteristics	Density (Mg m^{-3})	Gap for 50% detonation probability		P_g at 50% Gap
		No. of Cards	mm	
PBXW-115 (Aust.)				
Single batch cast low porosity	>1.79 (> 99.4% TMD)	86.5	22.0	6.3 GPa
Multiple batch cast low porosity	>1.79	83.5	21.2	6.4 GPa
Single batch cast high porosity	<1.70 (< 94.4% TMD)	87.5	22.2	6.3 GPa
PBXW-115 (USA) [1, 34]	1.79	129.5	32.9	4.7 GPa
Comp. B 60 RDX(Gr. A) / 40 TNT/ 1 Wax [AMRL, 15]	1.65 (open cast)		47.6	2.5 GPa
Comp. B 60 RDX(Gr. B) / 40 TNT/ 1 Wax [AMRL, 15]	1.67 (open cast)		51.1	2.0 GPa
Comp. B [34]	1.69 - 1.70 (cast,?)		52.5	1.6-2.0 GPa
	1.66 (pressed)			1.4 GPa
TNT (open cast, poured clear, mp 81- 82°C) [AMRL, 15]	1.56 (cast)		38.1	3.9 GPa
TNT [34]	1.61(cast)			4.4 - 4.6 GPa
	1.64 (pressed)			2.6 GPa
TNT[34, p 25] cast	1.58 (cast)			3.9 GPa
	1.58 (pressed)			2.0 GPa

Firstly, the shock sensitivity of PBXW-115 of both Australian and US origin is low compared to that of many conventional explosive fills based on RDX.

Secondly, the shock sensitivity of PBXW-115 (Aust.) appears to be appreciably less than that of its American counterpart. This possibly reflects the subtle changes in the properties of the RDX used in the formulations or else adventitious differences in the test configurations. To enable one to check for differences due to instrumentational effects, some supplementary data from LSGT measurements on the AMRL facility [15] have been included in Table 4; the results on the AMRL LSGT facility agree well with those from other facilities for similar materials, suggesting that differences due to the nature of the RDX in PBXW-115 (Aust.) and PBXW-115 (USA) are responsible for the differences in shock sensitivity.

Thirdly, there is very little difference between the relative shock sensitivity of charges of PBXW-115 (Aust.) of high density / low porosity (density 1.79 Mg m^{-3}, 99.4% TMD) and those from lower density / higher porosity (≤ 94.4% TMD) charges, suggesting that, over this range and at this charge diameter, no significant shock sensitization occurs by introducing voidage into these charges.

4. Discussion

4.1 Background

In the extended abstract submitted to the Tenth Detonation Symposium, David Kennedy and David Jones [7] introduced their paper modelling the shock initiation and detonation properties of PBXW-115 by detailing the characteristic features of high density, heterogeneous explosives in the following manner:-

In high density, heterogeneous explosives, the rate at which reaction can proceed within the detonation reaction zone is limited by the speed with which mass diffusion in the turbulent flow behind the shock front can bring the fuel and oxidizer together. As a result, the release of chemical energy in the detonation wave occurs throughout a reaction time frame or reaction zone which is relatively large in comparison to the initially advancing shock front in these types of formulations. Subsequent lateral expansion diverts a significant fraction of the released energy away from the zone supporting the detonation front while the attendant rarefaction can freeze out or slow down the chemical reactions before they can proceed to normal completion. Consequently, measured detonation velocities can be significantly lower than those predicted by planar one-dimensional thermodynamic equilibrium calculations, especially as the charge diameter approaches the critical or failure diameter. This behaviour is said to be "non-ideal".

In a similar vein, Forbes, Lemar, Sutherland and Baker [2] have compared their results on PBXW-115 (USA) [5] with our preliminary results on PBXW-115 (Aust.) [6] and have stated quite categorically that the performance differences between the two formulations may result from all or some of the subtle differences in the materials (particle size distribution, crystal size, shape and quality, crystal defects in the ingredients, charge density and composition). They have also pointed out that the current approaches to mathematical modelling, while giving excellent insight into the description of the ignition and detonation process of heterogeneous explosives [7, 23 - 26], are still insufficiently detailed to predict routinely the significant differences in detonation properties that do result from the different microphysical properties of these materials.

It is against this background that the material detailed in Sections 2 and 3 above can now be addressed.

4.2 Differences in Materials

Specification differences between the different types of RDX used to formulate PBXW-115 (Aust.) and PBXW-115 (USA) have already been covered. The point that Australian-made RDX , Grade A, Class 1, contains no detectable HMX (300 MHz ^{1}H-NMR) while its American equivalent, RDX Type 1, Class II probably contains 5-12% cocrystallised HMX, is interesting. From a formulator's point of view, the presence or otherwise of 2% HMX in the overall composition of PBXW-115 would appear of relatively small consequence; it may be expected to increase impact and shock sensitivity but, at that level, the anticipated effect would be small. However, the organic solid state is an intriguing chemical potpourri [35, 36] and Forbes has indicated [2] that included or coprecipitated HMX can be responsible for a large number of crystal defects in RDX and that defects can sensitize the initiation properties of RDX.

In as far as one can talk about the median particle size of a bimodal mix and attempt to relate changes in performance to particle size changes, shape or otherwise [2, 13, 37], the median particle size of the RDX component used in PBXW-115 (USA) has been estimated as 60 μm (mass basis) [2] and that of PBXW-115 (Aust.), 105 μm. There are many examples in the literature illustrating the effect of particle size on explosive performance.

Both Australian and American formulations contain AP from American sources, median particle size 200 μm, while the mean particle size of aluminium in the US formulation is ca. 5 μm [2] and that used in PBXW-115 (Aust.) is ca. 20-25 μm (Malvern Particle Size Analyser), Fig. 1.

4.3 Critical Diameter, Velocity of Detonation and Reaction Zone in PBXW-115

Anderson has shown that the failure diameter of PBXW-115 (USA) alters significantly with changes in the particle size of the bimodal RDX used in the formulations (quoted in [2]), a point which cannot be dismissed lightly in any comparative assessment.

This observation is similar to what has been reported by Moulard *et al.* [19] from unconfined cast-cured PBX formulations containing RDX (70%, by mass) in a polyurethane binder (30%, by mass) , Table 5.

Table 5: The Effect of Particle Size of RDX on Critical Diameter of Unconfined Charges of a Series of RDX / Polyurethane-based PBXs, Density 1.45 Mg m^{-3} [19, 20]

Original Authors' Designation/ Formulation	Median RDX Particle Size (μm)	Specific Surface Area ($m^2 g^{-1}$)	Critical Diameter (mm)	D ($m s^{-1}$)†
Monomodal, Fine, F	6	1.53	< 5 mm	7450
Monomodal Coarse, C	134	0.08	10-20 mm	7790 (linear) 7500 (elliptical)
Monomodal Very Coarse, VC	428	0.04	≥ 10 mm	Similar to C
Bimodal, F5 F 50%, VC 20%	127		5 mm	Similar to C
Bimodal, F2 F 20%, VC 50%	307		ca. 10 mm, < VC	Similar to C

† D. J. Whelan (1993): calculations on Moulard's published data.

From the results quoted in Sections 3.2.1 - 3.2.3, one can infer that the global rate of reaction under detonation conditions in PBXW-115 (USA), as described by Anderson and Leahy [1] and by Forbes *et al.* [5], would appear to be greater than that of PBXW-115 (Aust.).

The reason for this can be found in Jones and Kennedy's description of the detonation process [6, 7] and Eyring's explanation of the effect of confinement [14].

If two very similar systems, such as PBXW-115 (Aust. and USA), are compared and it is found that one system can sustain a detonation at a lower failure diameter or with

a higher V of D than the other, then such a result would suggest, a priori, that in the former case either the critical reaction zone is more compact or the reaction is proceeding at a faster rate. Eyring has related this to the theory of absolute reaction rates in chemical reactions [14].

4.3.1 The Concept of Reaction Zone: Unconfined Charges

The measured V of D of a cylindrical charge of a particular explosive formulation depends on the diameter of the charge and on the degree of confinement and the mathematical relationship between observed V of D and charge diameter has been an area of continuing investigation for over forty years.

From the early work summarised by Eyring *et al.* in 1949 [14], it was apparent that, for many ideal explosives, there appeared to be a linear relationship between V of D and the reciprocal of the diameter of the charge, of the form

$$V(d) = D\,(1 - [a / d]) \qquad \text{[Eq. 11a]}$$

or, in dimensionless form,

$$V(d) / D = (1 - [a / d]) \qquad \text{[Eq. 11b]}$$

where V(d) is the velocity of detonation of a detonating cylindrical charge, diameter d, D is the limiting value of the velocity of detonation for a charge of infinite diameter, and a is a constant characteristic of the explosive formulation and one which Eyring et al. related to the "reaction zone length" of the system.

However, for many explosives and for heterogeneous explosives in particular, the above relationship was seen to fall down, especially when the charge diameter approached the critical diameter, d_c. For this reason, Campbell and Engelke [24] introduced an additional term into the Eyring equation, which took the overall form

$$V(d) / D = (1 - [a / d] - [a\,d_c / d\,(d - d_c)]) \qquad \text{[Eq. 12]}$$

This relationship enabled a large bank of data to be rationalised successfully [24, 38] its main shortcoming being that one needs a considerable bank of data or should know the values of d_c and D before one can apply the equation to a given situation.

Chan [22] has related d_c to the radius of curvature, R, of the detonation front, through an empirical relationship

$$(d / R) = [1 + 6\,(d_c / d)^3] \qquad \text{[Eq. 13]}$$

giving one the opportunity to correlate V of D, d_c, d and R as required. More recently, experimental data presented by Cooper for charges with critical diameters up to ca.

20 mm [39] suggests that d_c can be estimated if one knows the magnitude of a, using a further empirical relation,

$$\log_{10} [d_c \text{ (mm)}] = 0.91 + 0.67 \log_{10} [a \text{ (mm)}] \qquad \text{[Eq. 14a]}$$

which translates to

$$[d_c \text{ (mm)}] \approx 8 \, [a \text{ (mm)}]^{2/3} \qquad \text{[Eq. 14b]}$$

In Section 3.2.2, the results for unconfined charges of PBXW-115 (Aust.) and PBXW-115 (USA) were found to follow an elliptical relationship ,

$$(V(d) / D)^2 = [1 - (a^* / d)^2] \qquad \text{[Eq. 15]}$$

where **a*** is a curve fitting constant, rather better than the simple linear relationship of Eq. 11b.

Analysis of the published data of several other heterogeneous explosive formulations indicated that a better fit could also be obtained from a plot of $(V(d) / D)^2$ vs. $(1 / d)^2$ than from a plot of $(V(d) / D)$ vs. $(1/d)$, in most cases (Tables 6 and 7); the only exception to this occurred in the formulation designated PBX-M#VF, where very fine RDX was used in the formulation.

Table 6: Analytical Description of the Relationship of the observed V of D and Charge Diameter for PBXW-115 (Aust. and USA)

PBXW-115 (Aust.) : Unconfined Charges, Charge Diameters: 80 mm to 200 mm.

$$[V, \text{meter s}^{-1}] = 5913.37 \{ 1 - (11.048 \times 10^{-3} / [d,\text{meter}]) \}$$
LLSQ Coefficient of Determination = 0.9680

$$[V, \text{meter s}^{-1}]^2 = (5641.77)^2 \{1 - (35.254 \times 10^{-3} / [d,\text{meter}])^2 \}$$
LLSQ Coefficient of Determination = 0.9833

PBXW-115 (USA) : Unconfined Charges, Charge Diameters: 38.7 mm to 69.1 mm

$$[V, \text{meter s}^{-1}] = 6193.4 \{1 - (6.849 \times 10^{-3} / [d,\text{meter}]) \}$$
LLSQ Coefficient of Determination = 0.9076

$$[V, \text{meter s}^{-1}]^2 = (5760.0)^2 \{1 - (18.325 \times 10^{-3} / [d,\text{meter}])^2 \}$$
LLSQ Coefficient of Determination = 0.9364

PBXW-115 (Aust. and USA) : Unconfined Charges, Variation of D. Jones (Section 3.2.2)

$$[V, \text{meter s}^{-1}] = 5968.3 \{ 1 - 0.14666 (d_c / d) \}$$
LLSQ Coefficient of Determination = 0.9072

$$[V, \text{meter s}^{-1}]^2 = (5671.6)^2 \{ 1 - (0.4555 \, d_c / d)^2) \}$$
LLSQ Coefficient of Determination = 0.9420 .

Table 7: Analytical Description of the Relationship of the observed V of D and Charge Diameter for Selected Explosives Compositions

Composition B: Unconfined Charges, (Malin et al.,[21]).

Formulation: RDX 63%, by mass, TNT 37% by mass , Slow Solidification Process.
RDX Particle Size: 80% < 400 μm
Charge Density 1.70 Mg m^{-3}, Charge Diameters: 5.71 mm to 20 mm.
Critical diameter: ca. 2 mm [21], 1.94 mm [24]
Original Authors' Designation: Malin Type 1.

$$[V, \text{meter } s^{-1}] = 7964.9 \{ 1 - (2.5989 \times 10^{-4} / [d,\text{meter}]) \}$$
LLSQ Coefficient of Determination = 0.9627

$$[V, \text{meter } s^{-1}]^2 = (7864.9)^2 \{1 - (1.5173 \times 10^{-3} / [d,\text{meter}])^2 \}$$
LLSQ Coefficient of Determination = 0.9970

RDX-based PBX-L#3: Unconfined Charges (de Longueville et al., [40])

Formulation: RDX 82.4%, by mass, Polyether-based Polyurethane Binder, 17.6% by mass , Cast cured.
Original Authors' Designation: Sample 3.
RDX Particle Size: not specified.
Charge Density 1.58 Mg m^{-3}, Charge Diameters: 10 mm to 30 mm.
Critical diameter: 6 mm.

$$[V, \text{meter } s^{-1}] = 8267.3 \{ 1 - (7.872 \times 10^{-4} / [d,\text{meter}]) \}$$
LLSQ Coefficient of Determination = 0.9536

$$[V, \text{meter } s^{-1}]^2 = (8035.5)^2 \{1 - (3.2406 \times 10^{-3} / [d,\text{meter}])^2 \}$$
LLSQ Coefficient of Determination = 0.9867.

RDX-based PBX-L#5: Unconfined Charges (de Longueville et al., [40])
Formulation: RDX 82.4%, by mass, Silicone Binder, 17.6% by mass , Cast cured.
Original Authors' Designation: Sample 5.
RDX Particle Size: not specified; as for PBX-L#3, above.
Charge Density 1.58 Mg m^{-3}, Charge Diameters: 10 mm to 30 mm.
Critical diameter: 7.5 mm.

$$[V, \text{meter } s^{-1}] = 7981.9 \{ 1 - (1.1781 \times 10^{-3} / [d,\text{meter}]) \}$$
LLSQ Coefficient of Determination = 0.9706

$$[V, \text{meter } s^{-1}]^2 = (7642)^2 \{1 - (3.950 \times 10^{-3} / [d,\text{meter}])^2 \}$$
LLSQ Coefficient of Determination = 0.9942

Table 7 (Contd): Analytical Description of the Relationship of the observed V of D and Charge Diameter for Selected Explosives Compositions

RDX-based PBX-M#C: Unconfined Charges (Moulard, et al. [18,19]).

Formulation: RDX 70%, by mass, HTPB/IPDI Binder 30% by mass, Cast cured.
Original Authors' Designation: Sample Monomodal, C (Coarse).
Mean RDX Particle Size: 134 μm.
Charge Density 1.45 Mg m^{-3}, Charge Diameters: 20 mm to 50 mm.
20 mm > Critical diameter > 15 mm.

$$[V, \text{meter } s^{-1}] = 7787.7\{1 - (2.378 \times 10^{-3} / [d,\text{meter}])\}$$
LLSQ Coefficient of Determination = 0.9768

$$[V, \text{meter } s^{-1}]^2 = (7495.4)^2 \{1 - (8.160 \times 10^{-3} / [d,\text{meter}])^2\}$$
LLSQ Coefficient of Determination = 0.9994

RDX-based PBX-M#VF: Unconfined Charges (Moulard, et al. [18,19]).

Formulation: RDX 70%, by mass, HTPB/ IPDI Polyurethane Binder 30% by mass,
Cast cured.
Original Authors' Designation: Sample Monomodal, VF (Very Fine).
Mean RDX Particle Size: 6 μm.
Charge Density 1.45 Mg m^{-3}, Charge Diameters: 10 mm to 50 mm.
Critical diameter < 10 mm.

$$[V, \text{meter } s^{-1}] = 7452.0\{1 - (0.1194 \times 10^{-3} / [d,\text{meter}])\}$$
LLSQ Coefficient of Determination = 0.9233

$$[V, \text{meter } s^{-1}]^2 = (7428.9)^2 \{1 - (1.344 \times 10^{-3} / [d,\text{meter}])^2\}$$
LLSQ Coefficient of Determination = 0.8102 ; linearity not deemed satisfactory.

HMX-based PBX-9404: Unconfined Charges (22,38)

Formulation: HMX 94%, by mass, Nitrocellulose 3% by mass, Tris (2-Chloroethyl) Phosphate 3% [34];
probably pressed .
Charge Density 1.846 Mg m^{-3}, Charge Diameters: 1.3 mm to 7 mm.
Critical diameter: ca. 1.2 mm [34], 0.55 mm [22]
V of D at infinite charge diameter, D : 8776 m s^{-1}, [34].

$$[V(d) / D] = \{1 - (0.1027 \times 10^{-3} / [d,\text{meter}])\}$$
LLSQ Coefficient of Determination = 0.8834

$$[V(d) / D]^2 = \{1 - (0.5196 \times 10^{-3} / [d,\text{meter}])^2\}$$
LLSQ Coefficient of Determination = 0.9319.

If one defines the parameter, **a**, from Eq. 11, as the Eyring reaction zone length factor, and the parameter, **a***, from Eq. 15, as the elliptical reaction zone length factor, one can see from Table 8 that the elliptical reaction zone length factor has a greater numerical value than the corresponding Eyring factor.

On the basis of the definitions of **a** and **a***, it is reasonable to assume that the numerical value of $(a^*)^2$ will reflect the surface area of the detonation reaction zone and that **a*** may be related to the experimentally determined critical diameter, d_c.

Table 8: The Properties of the Reaction Zone of PBXW-115 (Aust. and USA) and other Selected Non-Ideal Explosives, based on Data in Tables 6 and 7

Formulation	Eyring's Reaction Zone Length Factor, **a** (mm)	Elliptical Reaction Zone Length Factor, **a*** (mm)	Experimental Critical Diameter, (mm)
PBXW-115 (Aust.)	11.05	35.25	80
PBXW-115 (USA)	6.85	18.33	37.6
PBX-L#3	0.787	3.24	6
PBX-L#5	1.18	3.95	7.5
PBX-M#C	2.38	8.16	15
PBX-M#VF	0.12	(1.34)	<10
Comp. B (Malin)	0.26	1.52	2

In practice, it was found that a plot of **a*** vs. d_c followed a linear relationship,

$$d_c \text{ (mm)} = 2.298\ a^* \text{ (mm)} - 2.294 \qquad \text{[Eq. 16a]}$$

with a LLSQ coefficient of determination = 0.997.

In addition, it appears that those RDX-containing formulations made up with fine RDX have smaller reaction zone lengths than those related formulations made up with less fine RDX.

Eq. 16a appears to hold for RDX-based charges with values of d_c from 10 to 80 mm, although the close correspondence between the numerical value of the intercept (2.294) and the gradient (2.298) is no more than a fortuitous consequence of the LLSQ analysis.

Given that a plot of the relationship should pass through the origin (i.e. $d_c = 0$, $a^* = 0$), then

$$d_c \text{ (mm)} = 2.201\ a^* \text{ (mm)} \qquad \text{[Eq. 16b]}$$

with a LLSQ coefficient of determination = 0.994.

This relationship is consistent with one which can be deduced from a consideration of the combined data from PBXW-115 (Aust. and USA) in Table 6, where one can see

$$a^* = 0.4555\ d_c .$$

From Table 8, one can see that both the Eyring reaction zone length factor and the elliptical reaction zone factor for PBXW-115 (Aust.) are greater than the corresponding factors for PBXW-115 (USA). This implies that the reaction zone is more diffuse in the

Australian formulation and that smaller diameter charges of PBXW-115 (Aust.) may be less responsive to stimuli that lead to detonation than their US counterparts [14].

4.3.2 The Concept of Reaction Zone : Confined Charges

In Table 9, the results of Table 3 (Section 3.2.3) on the effect of brass confinement on failure diameter and on V of D are summarised.

Table 9: Analytical Description of the Relationship of the observed V of D and Charge Diameter for PBXW-115 (Aust. and USA): Confined Charges

PBXW-115 (Aust.) : Confined Cylindrical Charges, Charge Diameters: 20 mm to 50 mm.

Brass pipe, external thickness 3 mm :

Critical diameter : 24 ± 2 mm.

$$(V\,[160,3],\ \text{meter}\ s^{-1}) = 5662\,\{1 - (2.787 \times 10^{-3} / [d,\text{meter}])\}$$
LLSQ Coefficient of Determination = 0.9717, (5 coordinates)

$$(V\,[160,3],\ \text{meter}\ s^{-1})^2 = (5437)^2\ \{1 - (9.710 \times 10^{-3} / [d,\text{meter}])^2\}$$
LLSQ Coefficient of Determination = 0.9833, (5 coordinates)

Brass pipe, external thickness 5 mm :

Critical diameter : 24 ± 2 mm.

$$(V\,[160,5],\ \text{meter}\ s^{-1}) = 5607\,\{1 - (2.43 \times 10^{-3} / [d,\text{meter}])\}$$
LLSQ Coefficient of Determination = 0.8020, (10 coordinates)

$$(V\,[160,5],\ \text{meter}\ s^{-1})^2 = (5407)^2\ \{1 - (8.965 \times 10^{-3} / [d,\text{meter}])^2\}$$
LLSQ Coefficient of Determination = 0.762, (10 coordinates)

Statistically, these latter pair of equations represent data with a considerable scatter. From an experimental point of view, they reliably reflect not only the limitations of the experimental method but also the general trend of the data.

PBXW-115 (USA) : Confined Cylindrical Charges, Charge Diameters: 20 mm to 50 mm. Brass pipe. 2.5 mm and 5 mm thick [5].

Critical diameter : 2.5 mm Brass Pipe, 21 ± 2 mm.
5.0 mm Brass Pipe, 17.5 ± 2 mm.

Insufficient data available to estimate a limiting V of D at infinite charge diameter.

Compare these data with those for the critical diameters of unconfined charges of PBXW-115 (Aust.) and PBXW-115 (USA), 80 mm and 37.6 mm, respectively (Section 3.2.1).

The effect of confinement on the shock wave from PBXW-115 is similar to that from other explosives at large relative diameters, namely that when a shock wave crosses a boundary from one material (here, the detonating explosive) to another (here, the brass pipe), a shock wave will be sent into the brass pipe. At the same time, either a shock or a rarefaction wave will be reflected back into the explosive, depending on whether the first material (explosive) is less dense or more dense (more correctly, less or greater acoustical impedance, the product of density and sound velocity) than the second material (pipe) [14].

In effect, the reflected shock enhances the confinement of the reaction zone, decreasing the critical reaction zone length factor, described by either **a** or **a***, from 11.048 mm to 2.787 mm [comparing **a** values, from Tables 6 and 9] or from 35.254 mm to 9.710 mm [comparing **a*** values] (3 mm brass pipe), and, in effect, decreasing d_c .

4.4 Shock Sensitivity of PBXW-115

There are two main approaches to studying the shock sensitivity of explosives. These are based on the traditional gap tests developed at NSWC over many years [16] and on variations of the LANL Wedge Test [41- 44].

The experimental configuration of the AMRL LSGT has been described in Section 2.5, where the measured stimulus is an attenuated, (relatively) long, sustained shock, of duration in excess of 1 μs [41]. The Wedge Test records, as a measure of shock sensitivity, the so-called Pop plot [44], noting either the time taken for an explosive to run to detonation for a specified initial incident shock / distance profile or the distance that the shock wave must run before detonation occurs in relation to the initial incident shock pressure. The two techniques do not always give identical results, those from the Gap Test being regarded as giving a measure of the ease of initiation or ignition, those from the Wedge Test profile, giving a measure of the subsequent build-up to detonation.

As was mentioned in Section 3.2.4, the LSGT results (Table 4) using NOL-designed calibrated rigs [15, 16] indicate that the shock sensitivity of PBXW-115 (Aust.) is not affected by the porosity of the charge for charges with densities greater than 94% TMD and that PBXW-115 (Aust.) is less shock sensitive than PBXW-115 (USA). The minimum initiating pressure (50% frequency), $P_{50\%}$, required to detonate the steel-confined PBXW-115 (Aust.) was found to be 6.3 GPa, that for PBXW-115 (USA), 4.7 GPa.

Can this be explained? There is no unequivocal explanation of this at the present time; one must consider the type of the RDX used in the formulations, its relative particle size distribution and its particle shape.

There are particle size differences between the RDX blends used in the two formulations, PBXW-115 (Aust. and USA) (Sections 2.1 and 2.2) and it is reasonable to

assume that the shock sensitivity of the formulations is RDX-driven [6,7]. However, one is reluctant to attribute the considerable differences here solely to the effects of RDX-particle size, as the RDX particle size differences between the two formulations do not appear to be inordinately large [2, 3]. It is more plausible to attribute the difference to sensitisation due to the presence of HMX (possibly 5-12%) in the coarser RDX (Type B, Class 1) component in PBXW-115 (USA) or to changes due to particle shape [2, 45, 46].

In a related study, van den Steen and Verbeek [13] formulated two cast-cured HTPB/IPDI polyurethane-bound PBXs based on bimodal RDX (85% by mass); the formulation which they designated PRDX-I was made up of 56.1% RDX, particle size cut 200-500 μm, and 28.9% RDX, particle size cut 10-60 μm, while that designated PRDX-II was made up of 42.5% of each of these two RDX batches. They found that, in their NOL-styled LSGT rig, *PRDX-I, the batch with the smaller percentage of fine RDX, was considerably more shock sensitive ($P_{50\%}$ = 3.2 GPa) than PRDX-II, ($P_{50\%}$ = 3.7 GPa).*

In a subsequent investigation [37], these authors formulated a second series of PBXs, based on the above formulation. In one, they used a coarse RDX made up of miscellaneous, randomly-shaped, rock-like particles, median particle size 285 μm, admixed with a fine RDX, made up of small regularly shaped material, median particle size 17 μm, to give their formulation (AD); their second formulation (BD) had the same fine material mixed with a coarse component of larger median particle size, 460 μm, made up of more-or-less cleaved hemispheres of RDX.

Were the effects controlling shock sensitivity of similar formulations in the LSGT due mainly to differences in mean particle size, one would have expected the more coarse formulation (BD) to be more shock sensitive than (AD). However, the reverse was found - *the value of $P_{50\%}$ for the more coarse formulation (BD) in the LSGT was found to be 3.9 GPa, compared to that of (AD), 3.2 GPa.*

Similar trends were evident in the Wedge Test results. *At similar initiating pressures between 3.3 GPa and 4.5 GPa, the run to detonation in (BD), 20-30 mm, was much greater than that in (AD), at the same pressure - confirming that (AD) was more shock sensitive than (BD) in the range studied* [41,44].

Both formulations had a similar amount of the fine RDX, 30.6%, compared to coarse, 54.4%, and the difference in LSGT - shock sensitivity must be attributed to either to *particle shape differences rather than to particle size effects* and the possible shock impedance mismatch resulting therefrom [47] or to possible differences in HE / binder interactions and coating efficiencies [48]. In other words, the authors felt that the initiating sites are not due to those originating from void-type imperfections but rather to those originating from differences in crystalline form.

These results can be compared with those of Moulard et al. [18-20] who also investigated the shock sensitivity of RDX (70% by mass) / HTPB/IPDI Polyurethane (30% by mass) PBXs, using the Wedge Test.

At lowest impact pressure, 4.4 GPa, the coarsest monomodal formulation (RDX median particle size, 428 μm) had a much shorter run to detonation distance (i.e. was considered decidedly more sensitive) than the less coarse formulation (RDX median particle size, 134 μm) and the finest monomodal formulation (RDX median particle size, 6 μm) apparently failed to detonate. *However, at the highest pressure studied, 12.0 GPa, this trend was reversed;* although the distance / time profiles were similar for all three formulations, *the finest formulation was more sensitive than the coarser (134 μm) material, which, in turn, was more sensitive than the 428 μm RDX-based material.* In other words, once initiation had occurred, "build-up" proceeds more rapidly in the smaller particle sized, larger surface area material, which then appears the more shock sensitive.

In short, the relative particle size distribution of the RDX has an important role in determining the shock sensitivity of an RDX-containing PBX [49], just as it does in determining the V of D of a PBX charge (Tables 6 and 7, above) at a particular charge diameter. However, the extrapolation of the results from one RDX-based system to another appears fraught with difficulty.

Particle shape, crystallinity and crystal surface all interact to determine the actual sensitivity towards an incident shock.

There is a considerable body of evidence to confirm the proposal that formation of hot spots is more efficient and that the hot spots are longer lived in formulations made with coarser grades of HE [41, 50]; however, it is also recognised that, once ignition has occurred, build-up to detonation is strongly influenced by the surface area of the finer sized HE material [35, 51, 52].

In PBXW-115, the RDX component is relatively small, mass-wise, compared to the bulk of the formulation. In addition, one should also appreciate that the particle sizes of the coarse RDXs used in the work of van den Steen above [13, 37] are much greater than those used in PBXW-115 (Aust. and USA).

5. Summary

A study of the detonation performance of the non-ideal insensitive explosive filling, PBXW-115 (Aust.), has been undertaken and the results compared to those from its American counterpart, PBXW-115 (USA) / PBXN-111, an explosive of the same nominal composition but formulated with bimodal RDX of different type and slightly different particle size distribution.

The major findings of this work are as follows:-

(1) There are significant differences in the explosive performance of the two formulations.

(2) The limiting value of the velocity of detonation at infinite diameter, D, of PBXW-115 (Aust.) is in the range 5.64-5.91 km s^{-1}, the actual value depending on what is the true relationship between the experimental V of D and the diameter of the charge. This range of values is slightly less than that calculated for PBXW-115 (USA), 5.76 - 6.19 km s^{-1}, using experimental data reported by Forbes *et al.* (1989) [5].

(3) The major differences between the results from the two formulations relate not to values of D but to critical diameter and to relative shock sensitiveness (as measured in the Large Scale Gap Test).

(4) The critical diameter of unconfined PBXW-115 (Aust.) is ca. 80 mm; that of PBXW-115 (USA) is 38 ± 2 mm; the differences are not as pronounced in charges confined in brass tubes, however -- 24 ± 2 mm (3 and 5 mm thick brass tubes) for PBXW-115 (Aust.) vs. 21 ± 2 mm (2.5 mm thick brass tubes) and 17 ± 2 mm (5 mm thick brass tubes) for PBXW-115 (USA). These differences can be related to the relative reaction zone lengths which characterise the detonation zones in these and other heterogeneous explosives, and

(5) The shock sensitivity of PBXW-115 (Aust.), as measured by the minimum initiating pressure leading to detonation at the 50% frequency level ($P_{50\%}$) in the Large Scale Gap Test, is 6.3 GPa. The corresponding figure for the US formulation is 4.7 GPa.

Reasons for these differences have been advanced at various parts of the discussion, (Section 4).

For instance, it has been reported that the critical diameter of PBXW-115 (USA) varies significantly with different particle-sized RDX [2], a behaviour pattern shown to occur with other RDX-based PBXs [18-20, 40]. This is not unexpected because particle size indirectly affects the "reaction zone length", **a*** [Eq. 15], a factor which can be related to the dependence of the velocity of detonation of a cylindrical charge of a heterogeneous explosive on charge diameter and therefore critical diameter.

To add to that, factors which affect surface morphology have also been shown to affect the shock sensitivity of PBXs [37, 47, 50, 53-55], as they do a great number of other physical and chemical processes. Indirectly, the presence of HMX in RDX may have a role in this process, not only because of its greater shock sensitivity but rather because HMX induces crystal defects into RDX and defects in RDX enhance its shock sensitivity [2]. Microscopic voids, rough surfaces and cracks, dislocations, glide planes and distorted crystal habits in the initiating explosive component of the formulation are all potential sources through which energy-activating stimuli can initiate reaction [56]. Aspects of these problems are being investigated at AMRL and elsewhere.

The treatment of unconfined V of D data for PBXW-115 (Aust.) in this report relates to the experimental results obtained for cylindrical charges up to 200 mm in diameter (Sections 2.4.2 and 3.2.2) . Jones and Kennedy have predicted that, at much larger diameters, an enhanced detonation shock wave should be produced, driven by the

rapid oxidation of Al and the incompletely oxidized products of the RDX-driven detonation process by AP [6,7]. This remains to be tested, experimentally.

As an offshoot of this particular investigation, the authors have formalised a possible relationship between V of D, d and the zone reaction length factor, **a***. The relationship between (V of D / D) and (1/d) for many "non-ideal" explosives can be expressed in the form of an elliptical relationship of the form

$$(V(d))^2 / D^2 + (1/d)^2 / (1/a^*)^2 = 1 \qquad \text{[Eq. 15]}$$

and **a***, in turn, can be related to d_c by a simple non-dimensional variable,

$$d_c = 2.201\ a^* \qquad \text{[Eq. 16b]}$$

for a wide range of RDX-based explosive formulations.

When $d = d_c$, one finds, on combining Eq. 15 and Eq. 16b, the V of D at the critical diameter, V (d_c), is given by the Eq.17,

$$V(d_c) = 0.8908\ D \qquad \text{[Eq.17]}$$

If one uses this approach and can establish the value of D and the form of the relationship between V of D and d, then one can determine the value of d_c with a considerable degree of confidence.

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The critical diameter, detonation velocity and shock sensitivity of Australian PBXW-115

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ABSTRACT

A study of the detonation performance of the insensitive explosive filling, PBXW-115 (Aust.), has been undertaken and the results compared to those from its American counterpart, PBXW-115 (USA) / PBXN-111, an explosive of the same nominal composition but formulated with bimodal RDX of different type and somewhat differing particle size distribution.

The limiting value of the velocity of detonation at infinite diameter, D, of PBXW-115 (Aust.) is in the range 5.64-5.91 km s^{-1}, the actual value depending on the assumed relationship between the experimental V of D and the diameter of the charge. This range of values is slightly less than that calculated for PBXW-115 (USA), 5.76 - 6.19 km s^{-1}, using experimental data reported by Forbes et al. (1989).

The major differences between the results from the two formulations, however, relate not to values of D but to critical diameter and to relative shock sensitivity (as measured in the Large Scale Gap Test).

The critical diameter of unconfined PBXW-115 (Aust.) is ca. 80 mm; that of PBXW-115 (USA) is 38 ± 2 mm; the differences are not as pronounced in charges confined in brass tubes, however -- 24 ± 2 mm (3 and 5 mm thick brass tubes) for PBXW-115 (Aust.) vs. 21 ± 2 mm (2.5 mm thick brass tubes) and 17 ± 2 mm (5 mm thick brass tubes) for PBXW-115 (USA).

The shock sensitivity of PBXW-115 (Aust.) is 6.3 GPa, the explosive shock wave pressure which has been determined experimentally to result in a 50% probability of detonation in the Large Scale Gap Test. The corresponding figure for the US formulation is 4.7 GPa.

Reasons for these differences are advanced.

The Critical Diameter, Detonation Velocity and Shock Sensitivity of Australian PBXW-115

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(DSTO-TR-0076)

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